Quark Mixing at nuMC Experiments

Bruce King
Brookhaven National Laboratory
bking@bnl.gov

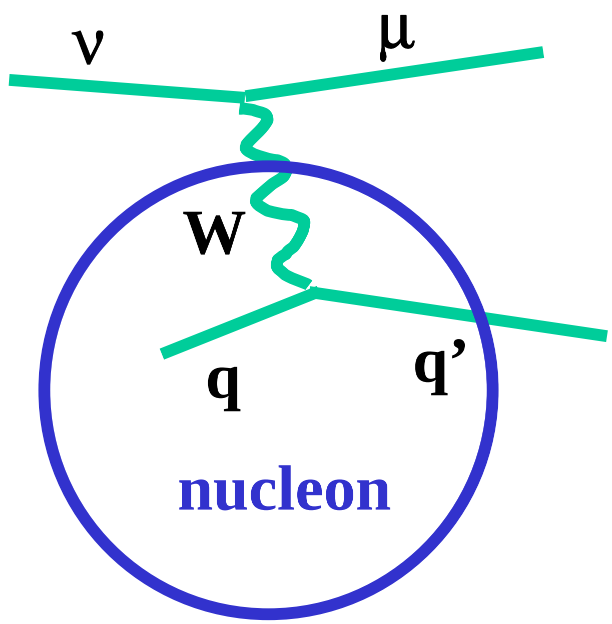
Outline:

- Motivation
- Experimental overview: beam & detectors
- Summary of potential neutrino interaction measurements
- CKM measurements from c,b production
- Top production?
- Conclusions

MOTIVATION

WHY CKM MEASUREMENTS USING NEUTRINOS ARE ENTIRELY UNIQUE & COMPLEMENTARY

νN DIS

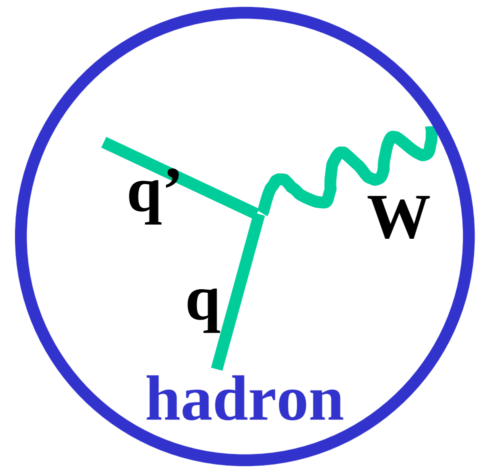


external W probe

fairly high Q => “quasi-free” quarks

measure several $|V_j|^2$

All other CKM measurements



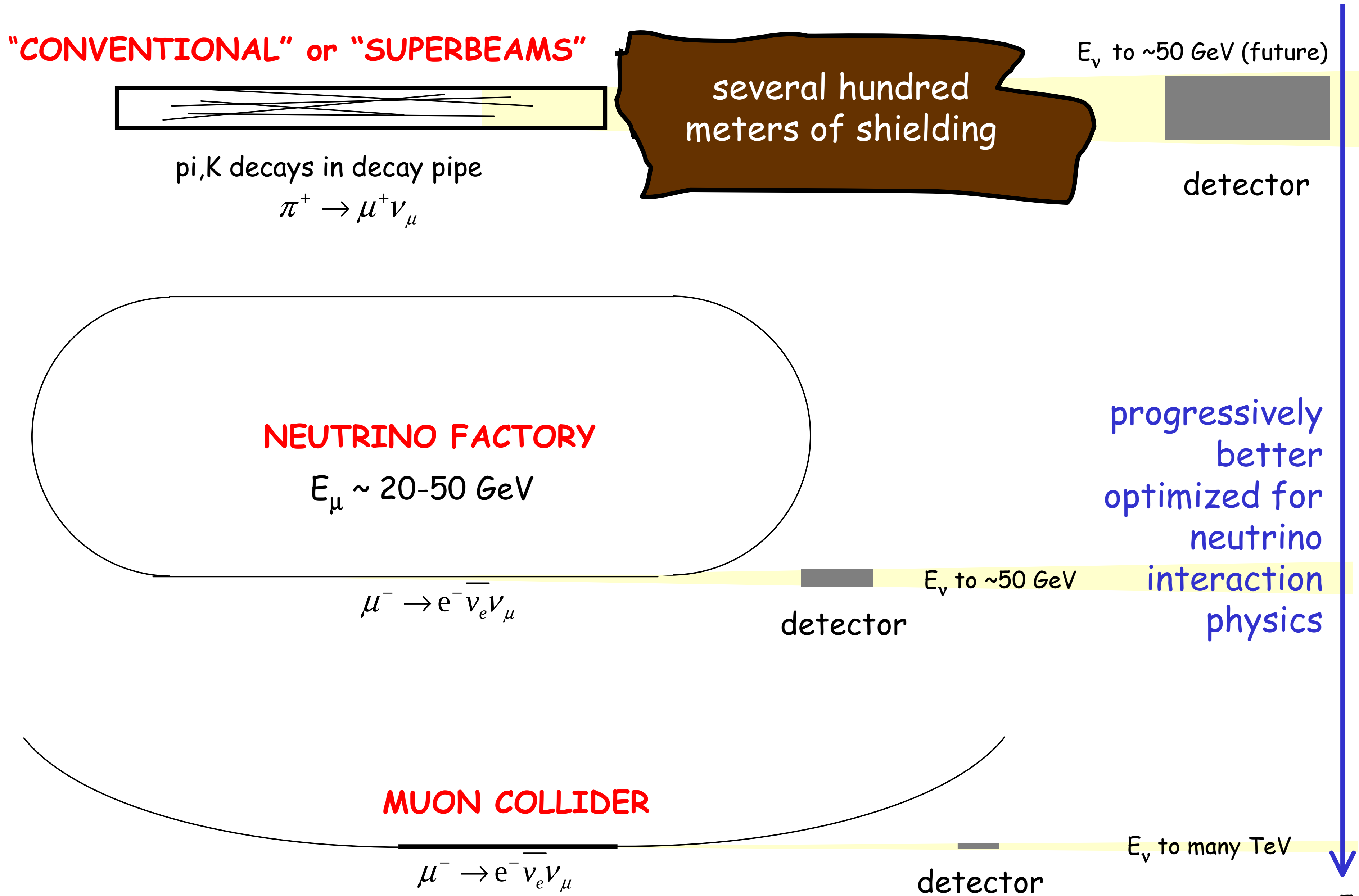
internal W interaction

lower Q => “messier” initial state

usually measure $V_j V_k^*$ interference terms

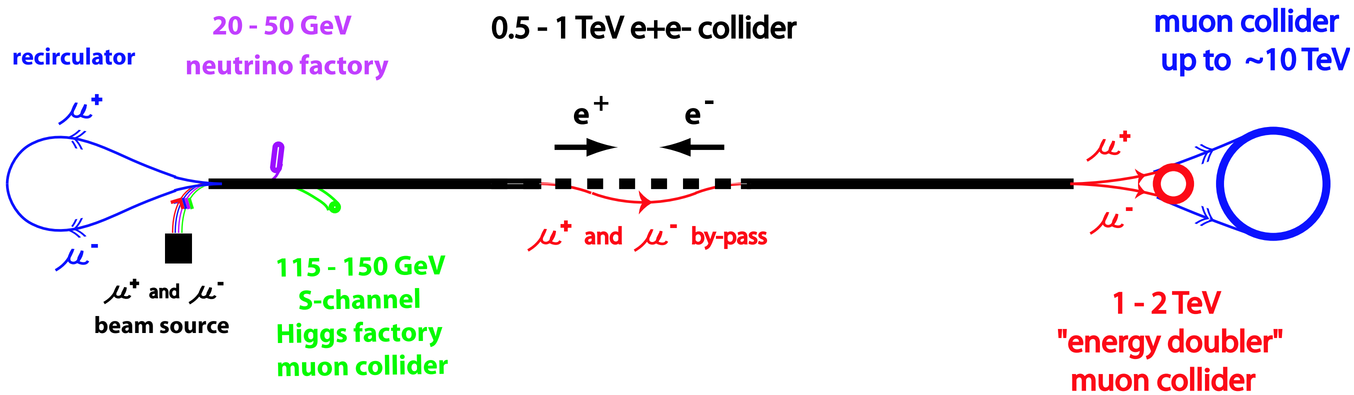
NEUTRINO BEAMLINES

TYPES OF ACCELERATOR-BASED NEUTRINO BEAMS



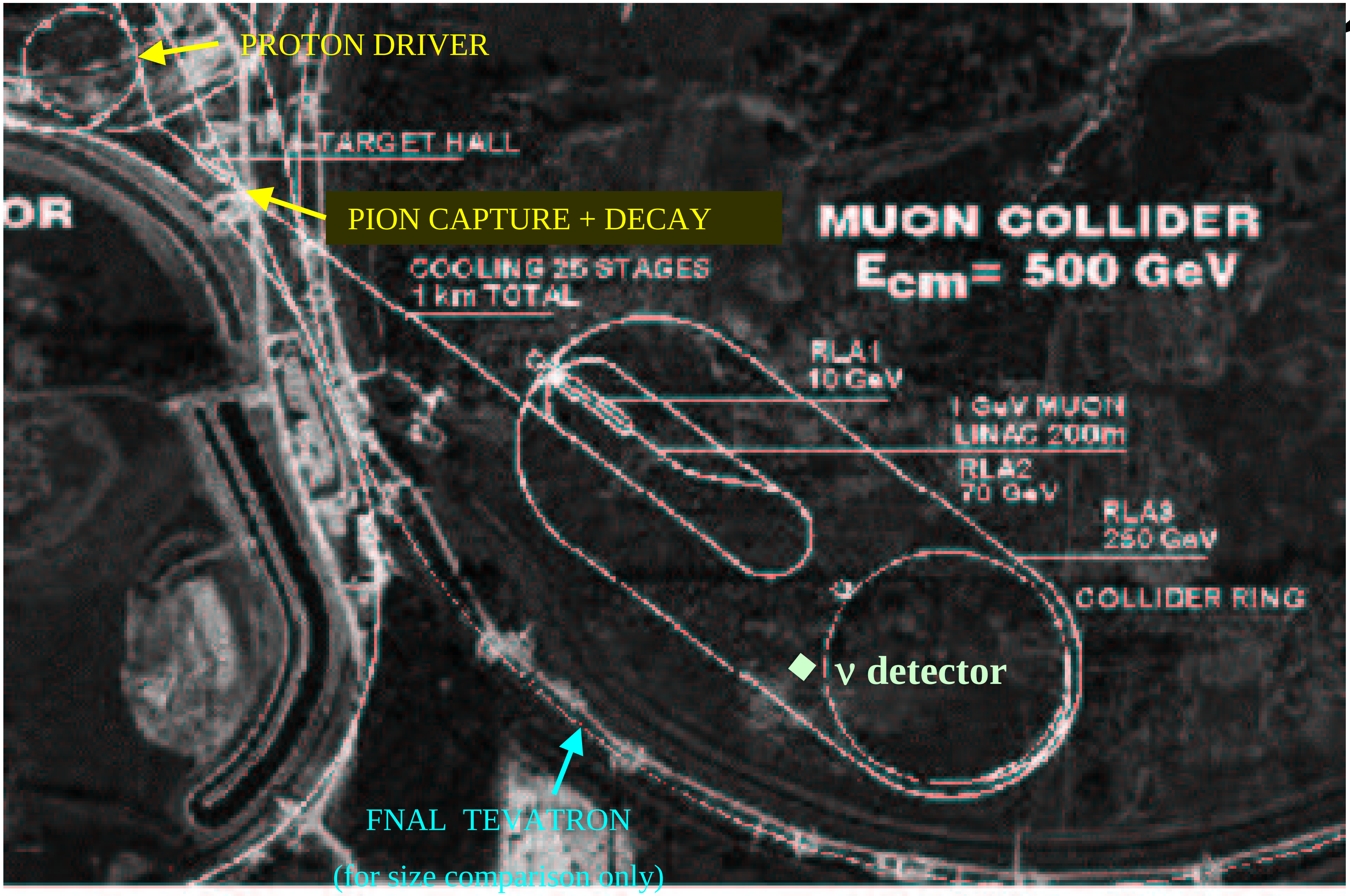
A POTENTIAL REALIZATION: LINEAR e^+e^- COLLIDER + MUON COLLIDER

First discussed by D. Neuffer, H. Edwards & D. Finley in Proc. Snowmass'96



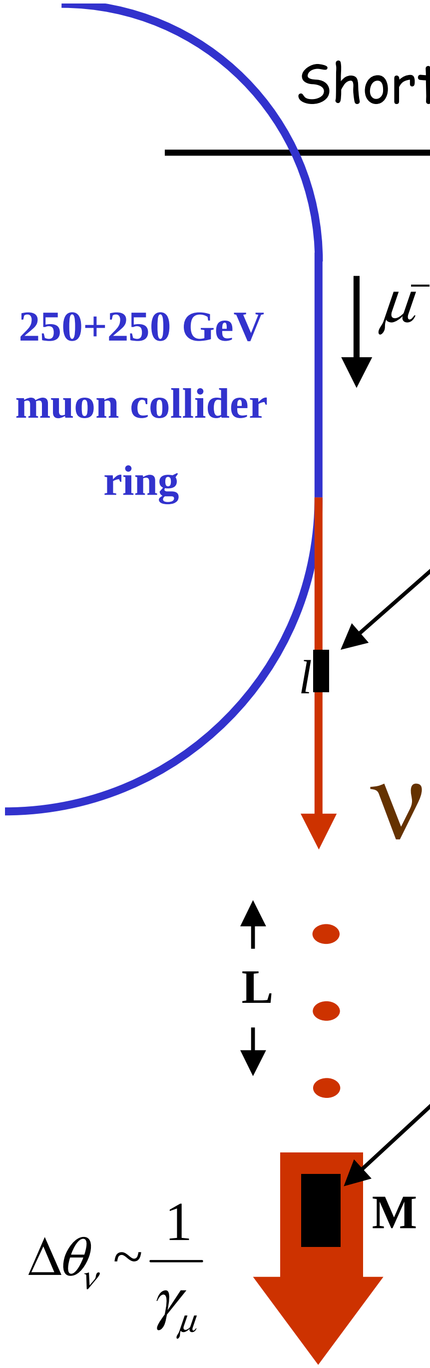
(M1+M3 joint session, Tuesday am, 17 July)

The Parts of a Muon Collider



Ref. "Status of Muon Collider Research and Development and Future Plans", the Muon Collider Collaboration (108 authors), to be published in Phys. Rev. Special Topics - Accelerators and Beams

Short Baseline (SB) & Long Baseline (LB) Experiments



SB general purpose detector

5 x 10^7 x l [g.cm^-2] events/year* WOW

2.6	$\nu_\mu - \mathrm{CC}$
0.8	$\nu_\mu - \mathrm{NC}$
1.4	$\bar{\nu}_e - \mathrm{CC}$
0.5	$\bar{\nu}_e - \mathrm{NC}$

LB detector for ν oscillations

$$3 \times 10^7 \times \frac{M[\mathrm{kg}]}{(L[\mathrm{km}])^2} \text{ events/year*}$$ WOW

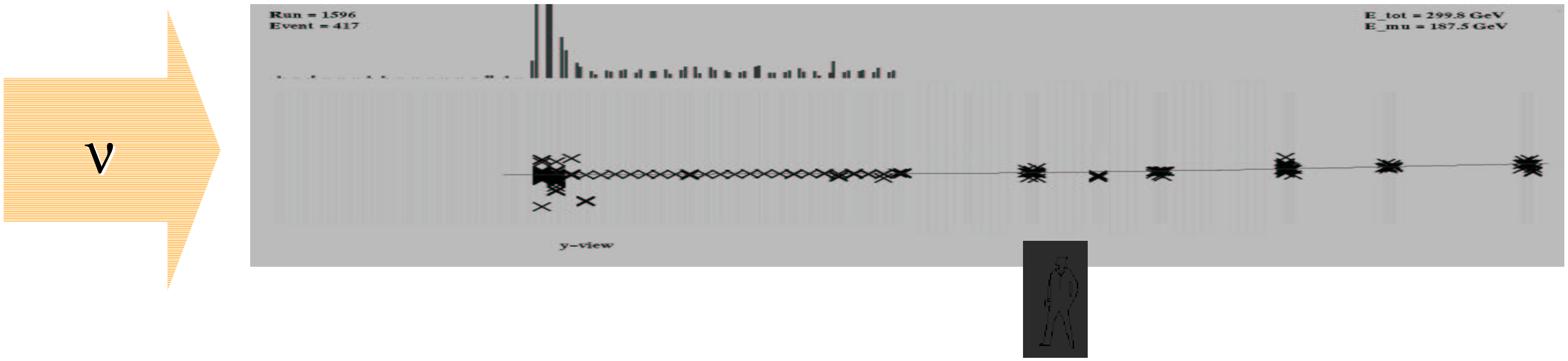
1.4	$\nu_\mu - \mathrm{CC}$
0.4	$\nu_\mu - \mathrm{NC}$
0.7	$\bar{\nu}_e - \mathrm{CC}$
0.2	$\bar{\nu}_e - \mathrm{NC}$

*assumes 250+250 GeV muon collider, 200 m straight section & 6×10^{20} ν^-/year

NOT YOUR GRANDMA'S NEUTRINO DETECTOR ...

Today's High-Rate Neutrino Detector (FNAL Lab E)

(based on design concepts from c. 1960)



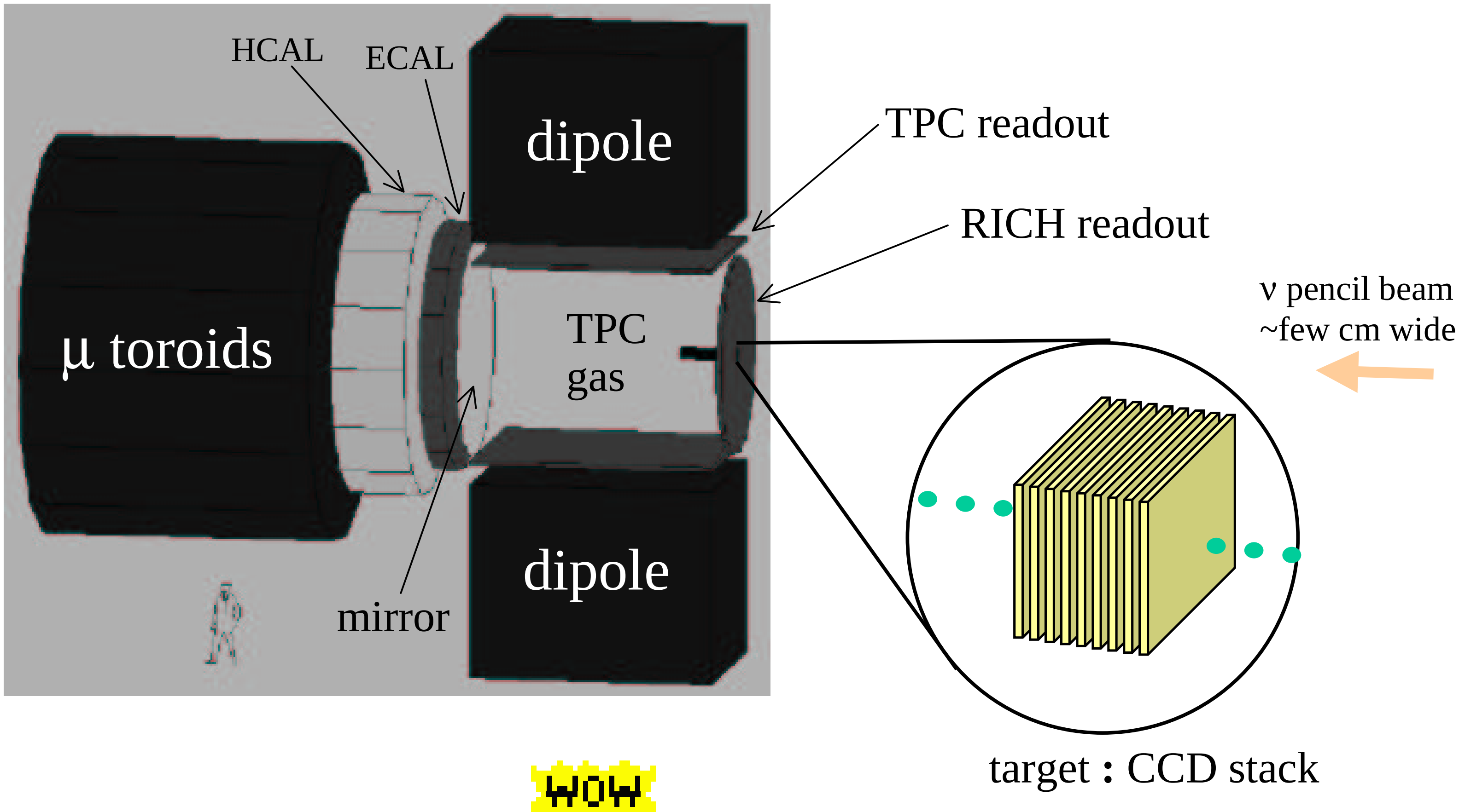
- 690 ton calorimetric ν target => $O(10^6)$ events/year
- "minimalist" event reconstruction:

3 variables for charged current (CC) events: E_{had}, p_μ & θ_μ

1 variable for neutral current (NC) events: E_{had}

At muon colliders, this can be replaced by … (next slide)

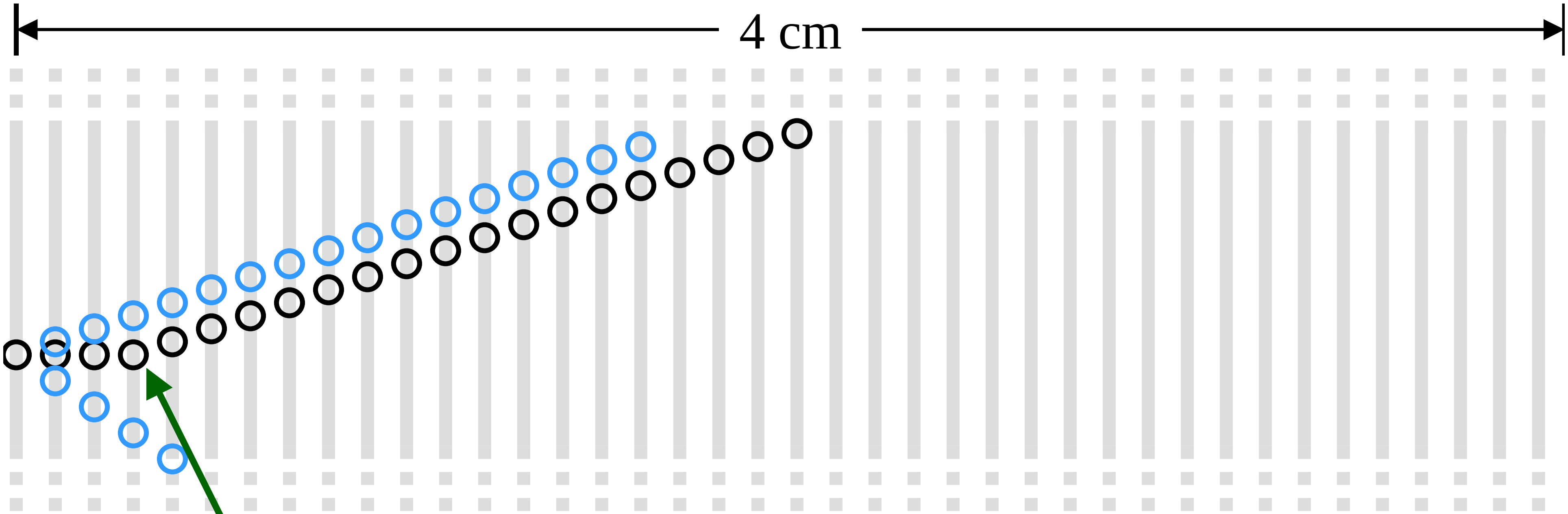
A High Performance, General Purpose SB Detector*



- HUGE statistics: 50 g/cm^2 target => ~10^{10} interesting events in 3 years
- outstanding event reconstruction: CC & NC event kinematics, full particle ID includes excellent vertexing of charm, beauty hadrons

*ref: BJK, "Neutrino Physics at a Muon Collider", FNAL Workshop, Nov.'97, AIP Proc. 435

Excellent vertex tagging for c, b and τ's!



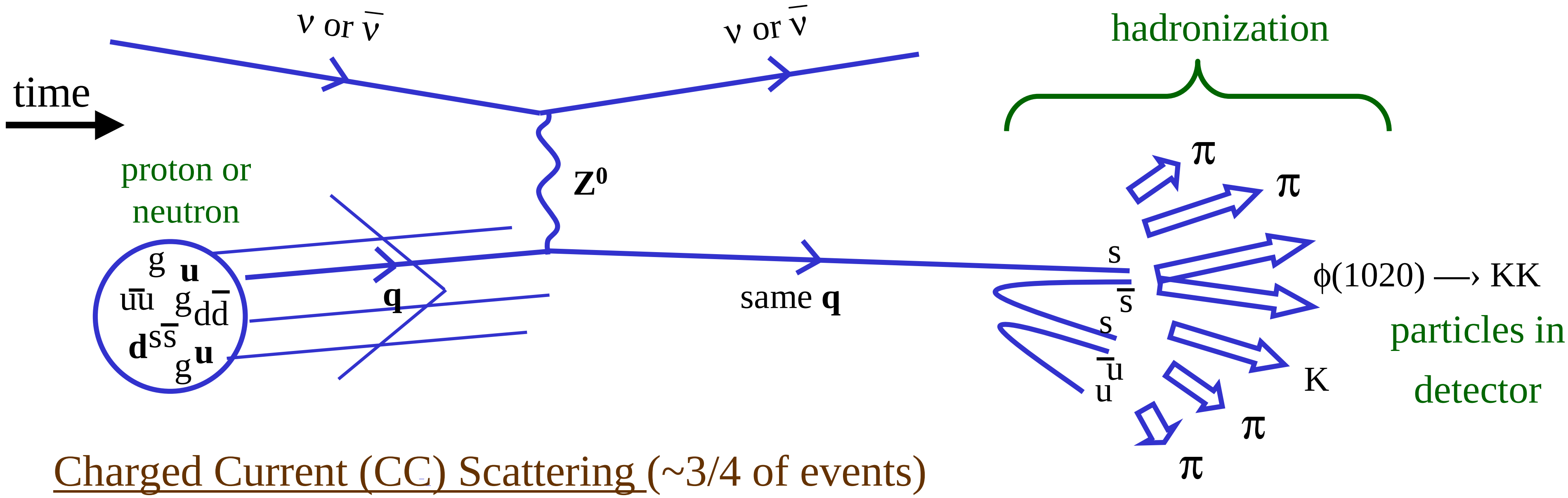
1-prong charm & tau decays made easy!

c.f. best collider vertexing so far
(SLD detector, same scale)

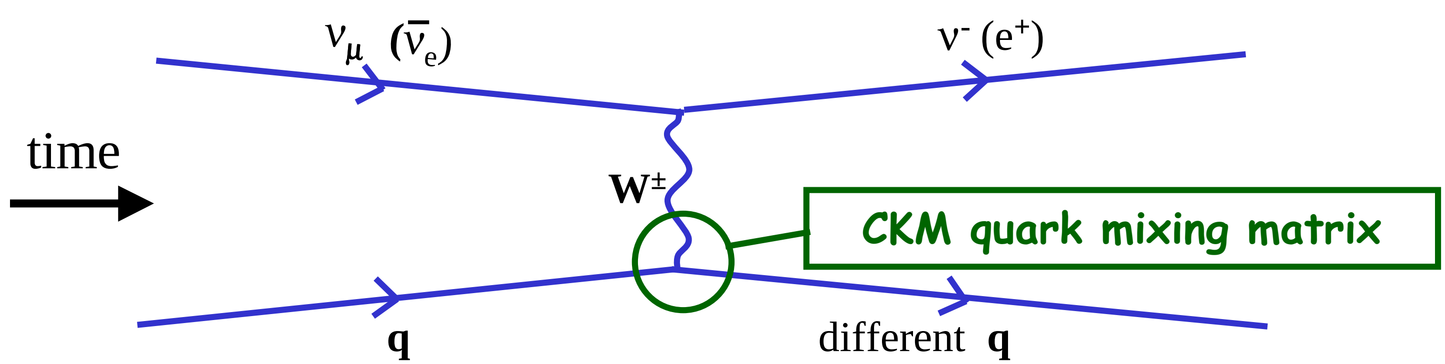
NEUTRINO INTERACTION PHYSICS FROM MUON STORAGE RINGS

νN DIS: testing ground for the weak interaction OR 3 simple probes of a complicated target

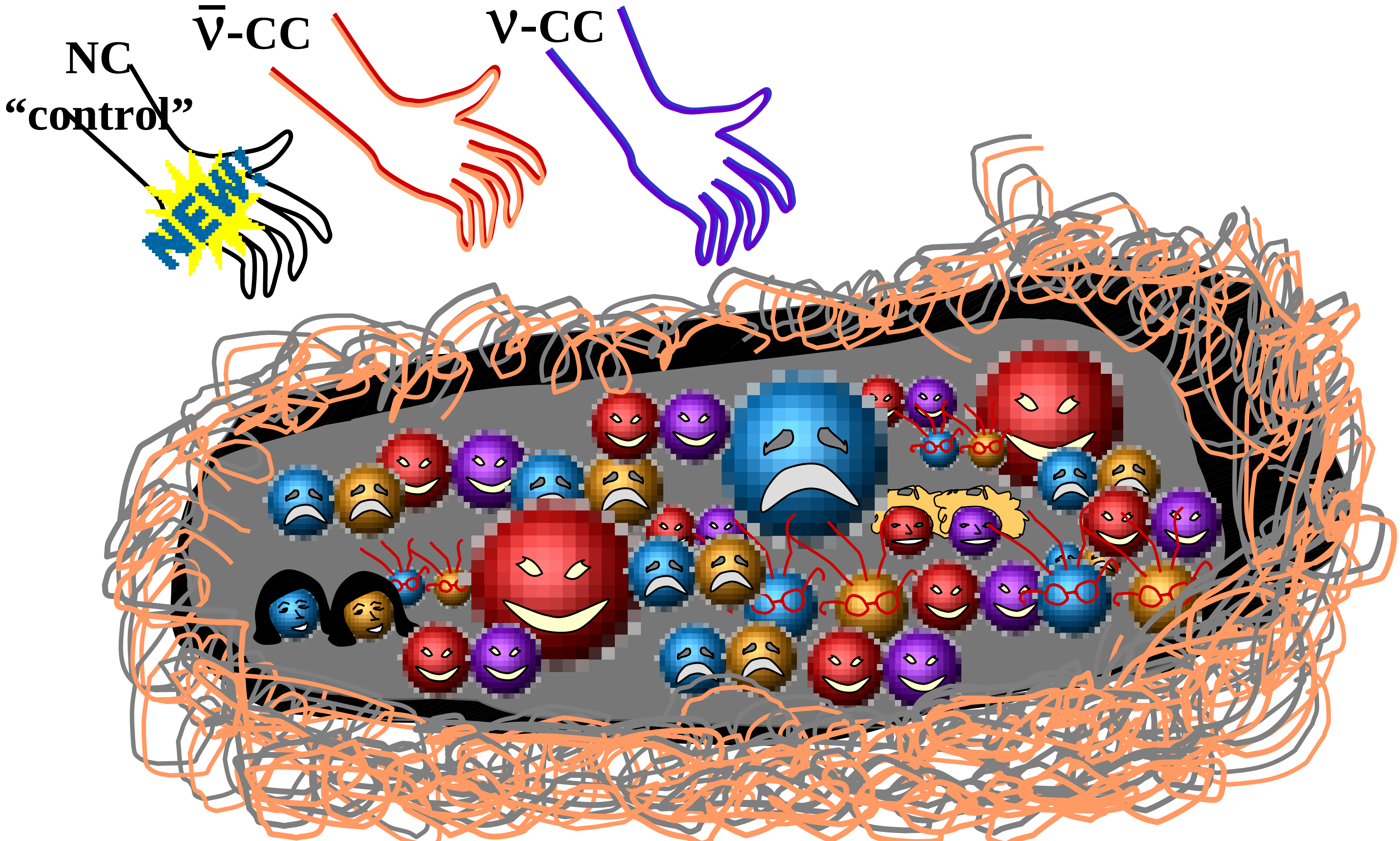
Neutral Current (NC) Scattering (~1/4 of events)



Charged Current (CC) Scattering (~3/4 of events)



An artist's conception: 3 probes of the nucleon:



Neutrino Interaction Topics at Muon Storage Rings

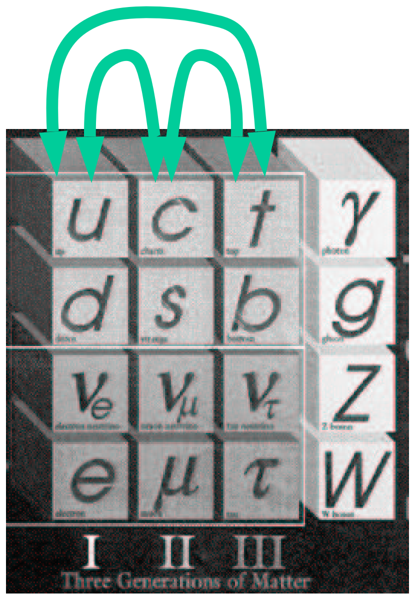
Ref. **"The Potential for Neutrino Physics at Muon Colliders and Dedicated High Current Muon Storage Rings",** Bigi, Bolton, Formaggio, Harris , Kayser, King, McFarland, Morfin, Petrov, Schellman, Shrock, Spentzouris, Velasco & Yu, to be published as a Physics Report, preprint available at Snowmass on Muon Collaboration's "Recent Reports" CD.

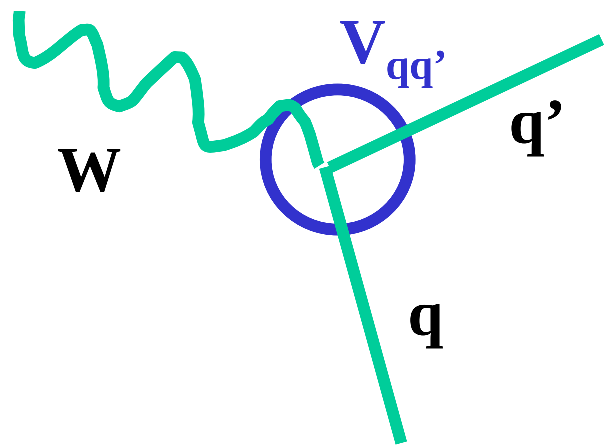
- **CKM measurements**
- determine detailed quark-by-quark structure of nucleon, including spin
- precise QCD tests
- precise tests of electroweak theory
- a new realm to search for exotic physics processes
- a powerful charm factory
- a new laboratory to study nuclear physics with neutrino beams

MEASUREMENTS OF QUARK MIXING & THE CKM MATRIX

Quark Mixing: Poorly Understood & Poorly Measured

• Charged current (CC) weak coupling between different quark generations is not seen in QCD, EM, NC or CC with charged leptons. **WHY?**

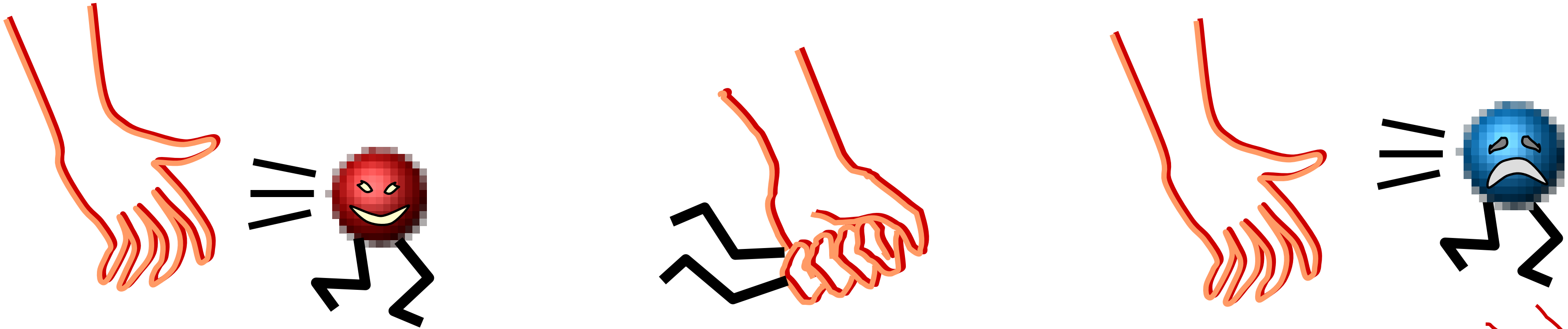


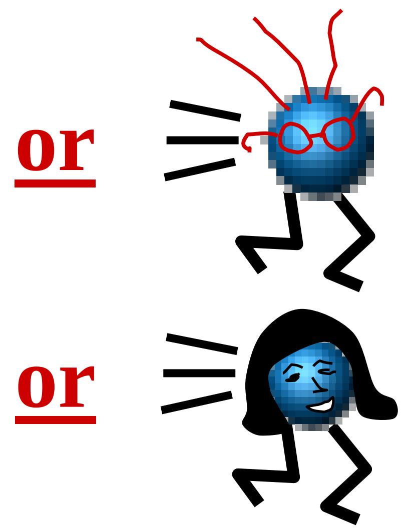


• SM hypothesis: 3x3 $V_{qq'}$ is <u>unitary</u>, the “CKM matrix”.

• CP violation: particle properties ≠ anti-particle properties. **WHY?** <u>Unconfirmed</u> SM explanation/parameterization is a complex phase in the CKM matrix. (But now have BaBar results - hot off the press)

Artists Conception: Quark Mixing in Action!





With mixing probabilities…*

	d	s	b
u	0.95	0.05	1×10^{-5}
c	0.05	0.95	0.002
t	1×10^{-4}	0.001	1

*neglecting quark masses

Summary of Experimental Method

- Measure the fractions of c & b quark production in CC interactions => absolute squares of CKM elements, up to mass threshold suppression and other corrections
- Systematic handle: separate valence and sea quark contributions by comparing neutrino vs. antineutrino rates.
- Prototypical analysis is extraction of $|V_{cd}|$ in today's neutrino experiments.

CURRENT UNCERTAINTIES IN QUARK MIXING PROBABILITIES & "GUESSTIMATED*" UNCERTAINTIES WITH 10^{10} ν INTEREACTIONS

*values from Bigi et al.

	d	s	b
u	0.1%	1.6%	60% ~3%
c	14% ~1%	31% ~3%	11% ~3%
t	25%	40%	30%

d→c

$O(10^8)$ events

s→c

$O(10^8)$ events

s(x) from NC

needs s tagging

u→b

$O(10^4)$ events

with b threshold

c→b

$O(10^4)$ events(?)

threshold very impt.

c(x) from NC

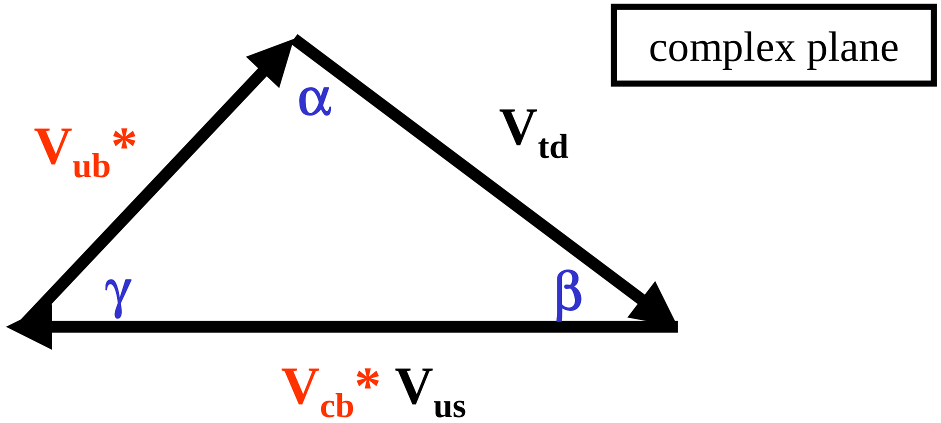
d, s→t

dramatic improvements

possible at very high E_ν

Not bad !!

Following on from the B Factories



The B factories etc. are trying to measure the angles α, β & γ to confirm that the unitarity triangle really ***is*** a triangle:

$$\beta + \alpha + \gamma = 180^o$$

feasible hard to measure

WOW

This test would ***benefit enormously*** from O(3%) measurements of the sides $|V_{ub}|$, $|V_{cb}|$ at a SB neutrino experiment !!

THOUGHT CANDY: CKM MEASUREMENTS WITH 50 TeV NEUTRINO BEAMS

Example of 100 TeV Muon Collider being Discussed at Snowmass

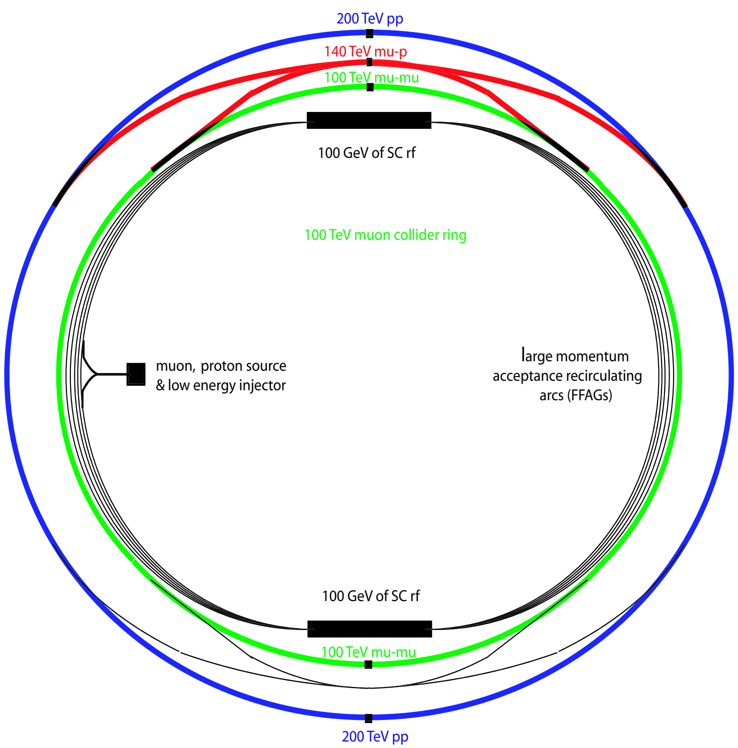
(was M1 Session last Saturday am)

Neutrino radiation => new, very isolated lab. for high luminosity Very Large Muon Collider (VLMC).

On balance, technical difficulties probably not much worse than for lower energy muon colliders.

(slightly less cooling needed; recent 30 TeV final focus design by Raimondi)

Schematic Layout showing Acceleration,
Muon Collider, Proton Collider & mu-p Collider



VLMC + VLHC symbiosis:

- ✓ common magnet R&D
- ✓ same tunnel, or side-by-side
- ✓ common acceleration to ~50 TeV/beam
  - ➢ full energy for muon collider
  - ➢ ~½ energy for hadron collider
- ✓ mu-p collisions at E_{CoM} ~ 140 TeV


The potential neutrino
experiments at a 100
TeV muon collider can
be compared to a
super-luminous HERA

Comparison between HERA & the Neutrino Beams from Very High Energy Muon Colliders

For the ν beam:

$$\underbrace{\mathbf{L}\,[\mathrm{cm}^{-2}.\mathrm{s}^{-1}]}_{\text{Luminosity}} \sim \underbrace{\overset{6 \times 10^{23}!}{N_{\mathbf{Avo}}}}_{\text{Avogadro's \#}} \;\; \mathrm{x} \;\; \underbrace{n_{\mu}[\mathrm{s}^{-1}]\,.\,f_{\mathbf{ss}}}_{\text{decays/sec in str. sec.}} \;\; \mathrm{x} \;\; \underbrace{\mathbf{l}\,[\mathrm{g.cm}^{-2}]}_{\text{target mass/area}}$$

Facility	$E_{\mathbf{CoM}}$	LUMINOSITY*	
HERA (2000 upgrade)	332 GeV	$7.10^{\mathbf{31}}$ $\mathrm{cm}^{-2}.\mathrm{s}^{-1}$	lifetime total of 1 inverse **femto**barn
10 TeV mu collider	0 to 97 GeV	$3.10^{\mathbf{38}}$ $\mathrm{cm}^{-2}.\mathrm{s}^{-1}$	3 inverse **zepto**barn/year
100 TeV mu collider	0 to 306 GeV	$7.10^{\mathbf{36}}$ $\mathrm{cm}^{-2}.\mathrm{s}^{-1}$	70 inverse **atto**barn/year

* n_μ as in HEMC'99 workshop straw-man parameter sets; f_{ss}=0.02, 0.01 for 5,50 TeV ν beams; **l** = 300 $\mathrm{g.cm}^{-2}$

WOW! A million times the luminosity!

Cribbing off HERA Studies ...

Process	HERA (1 inverse femtobarn)	MURINE (1 inverse **zepto**barn)
exotica with v. small cross-sections (σ)	may be limited by luminosity X	luminosity no problem!
W, Z boson production	σ ~ 40 fb => ~40 events X Gaemers, Godbole & van der Horst*	σ << 40 fb, O(10^{6}) events at highest E_{μ} ?
Higgs production (M_H~120 GeV)	σ ~ O(1 fb) => ~O(1) event X Gaemers, Godbole & van der Horst*	up to O(10^{6}) events at highest E_{μ}!
top quark production	σ ~ O(1 fb) => ~O(1) event X Baur & van der Bij; Ali et al.*	up to O(10^{6}) events at highest E_{μ}=> $\|V_{td}\|$, $\|V_{ts}\|$, $\|V_{tb}\|$!
b quark production	$\sigma_{\mathbf{c->b}}$ ~ 12 fb => ~12 events X $\sigma_{\mathbf{u->b}}$ ~O(1) fb => O(1) event X Godbole & Treichal; Ali et al.*	O(10^{7}) events => best $\|V_{cb}\|$! O(10^{6}) events => best $\|V_{ub}\|$!

CKM

*all refs.: Hamburg 1987, Proceedings DESY Workshop on Physics at HERA

CONCLUSIONS

Neutrino beams from muon colliders &/or neutrino factories hold the promise of unique direct measurements of the CKM elements $|V_{cd}|$, $|V_{cs}|$, $|V_{ub}|$ & $|V_{cb}|$ and, at the highest muon collider energies, possibly even $|V_{t.}|$.